

# TETHER DESIGN FOR SPACE DEBRIS TOWING

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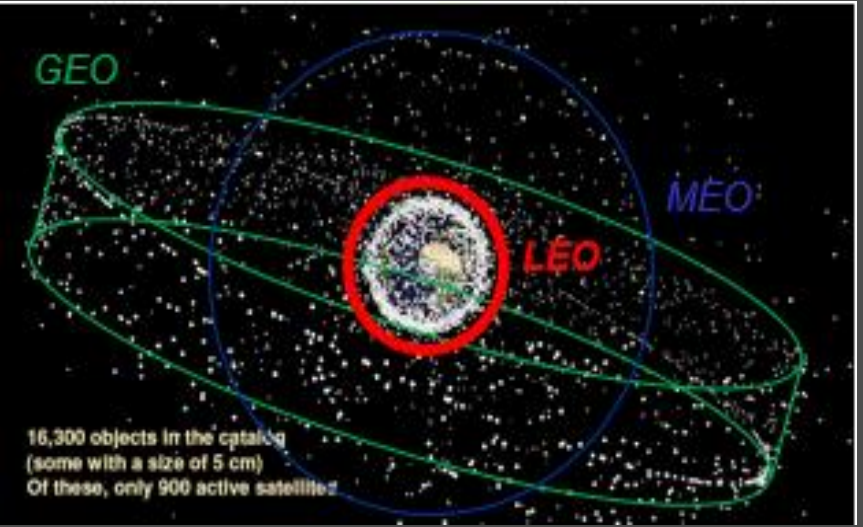


## Towing Tethers

### Mission Overview

#### Tethers' exploitation for space debris mitigation/remediation

- TETHER:** long thin cable – mechanical connection – not withstanding compressive loads
- MITIGATION:** tethered devices installed on-board (drag augmentation, EDTs)
- REMEDICATION:** elastic connection established in-orbit by means of different capture strategies: nets, harpoons, tentacles, grasper, etc.



### Debris Tethered-Disposal Options

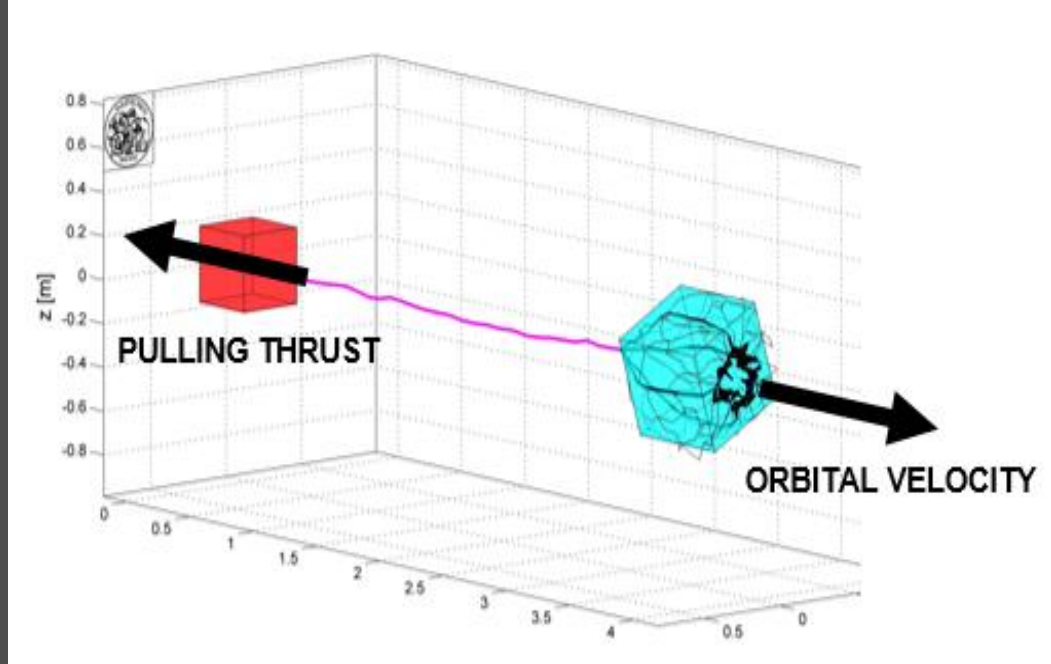
#### TOWING TETHERS:

- Non-conductive
- Exploiting chaser thrusters to de/re-orbit system

#### ELECTRO-DYNAMICS TETHERS:

- Conductive
- Exploiting Lorentz Force through interaction with magnetic field and ionosphere

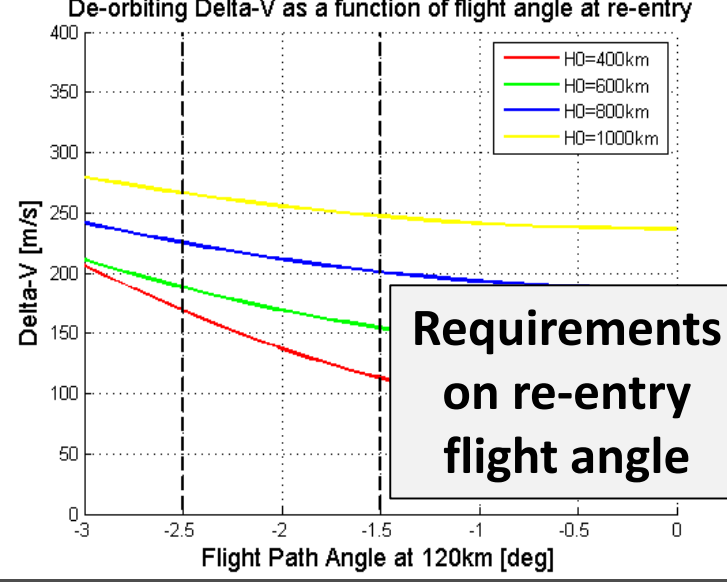
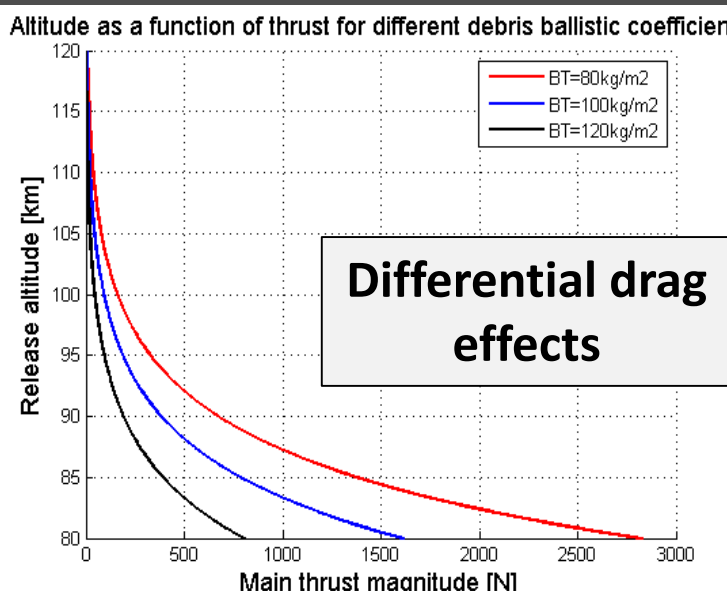
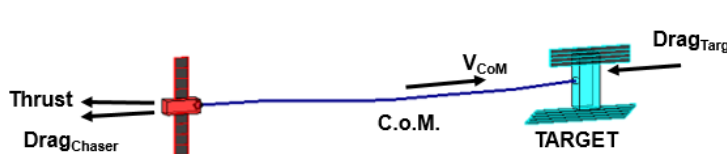
#### Capture net and towing tether de-orbiting concept



### Towing Tethers' Dynamics and Control Simulations

#### MODEL

- 6 DOF end-bodies with flexible appendages
- Discretized viscoelastic model for flexible tether
- Perturbations: air drag, solar pressure, gravity



#### Operations sequence for high-thrust controlled re-entry

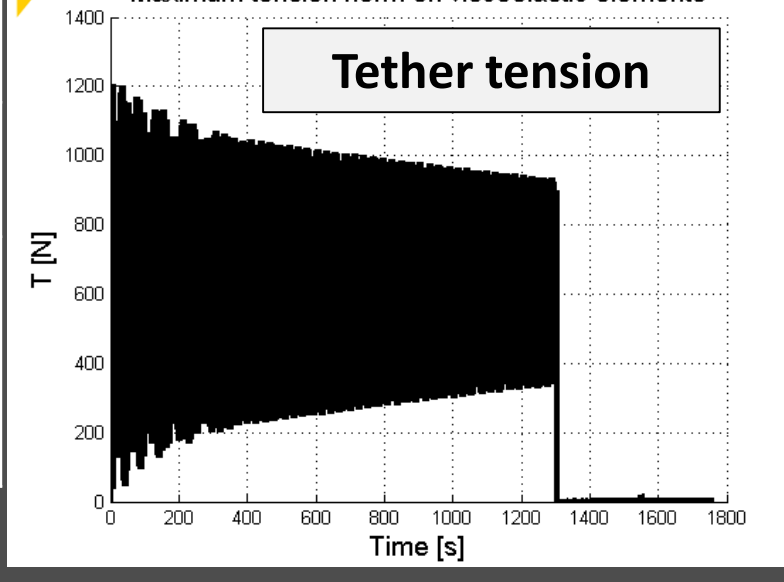
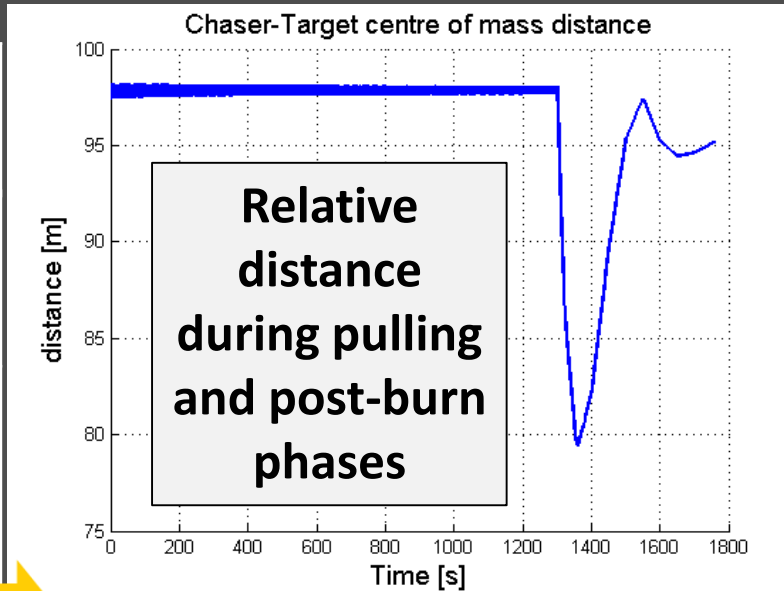
- Stabilization/Pre-tensioning
- Dragging
- Post-burn control
- Tether cut and CAM (if needed)

#### GNC

- Closed-loop GNC with feedback on tether tension and relative distance
- RCS (PWM) for relative maneuvering
- No control on tether length (fixed-length)

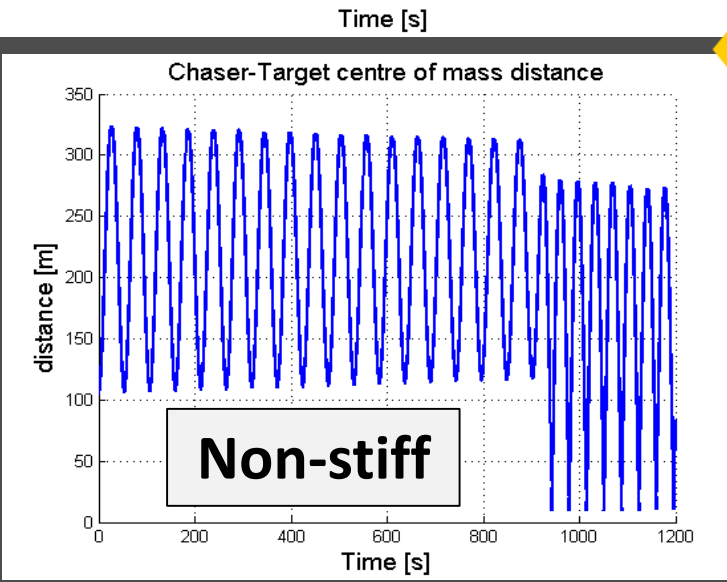
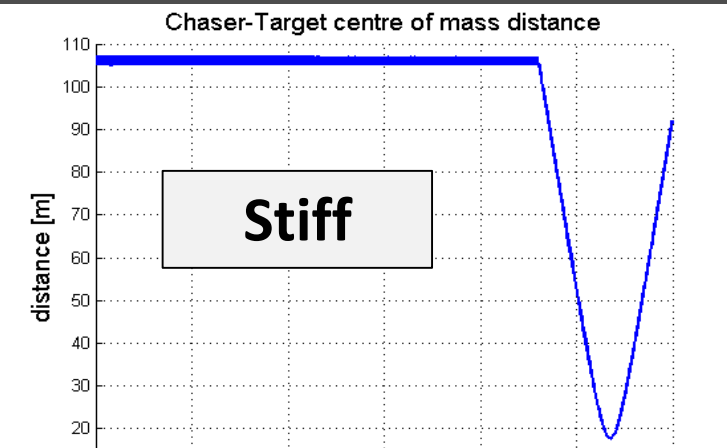
#### STIFF TETHER CASE

Mass [kg]	Chaser = 1300 Target = 5000 Tether = 0.58
Initial orbit altitude [km]	600
Thrust [N]	Main = 800 RCS = 25
$\Delta V$ [m/s]	160
Flight angle at 120km [deg]	-1.6



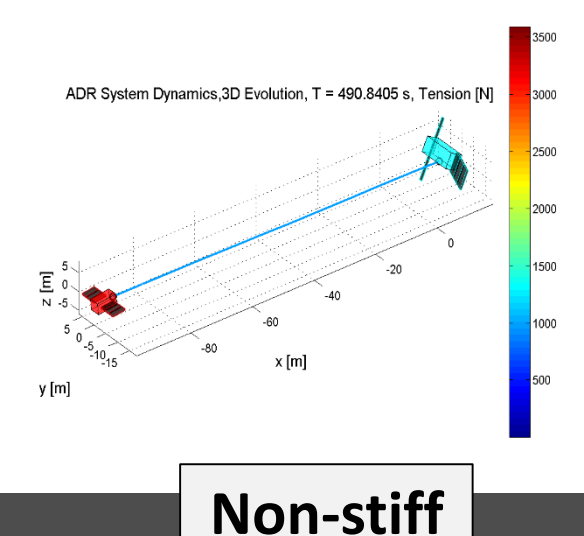
### Fundamental influence of tether elasticity on dynamics behavior

CASE	Stiffness [N/m]	Damping [Ns/m]	PROS	CONS
Stiff	1.57e3	0.3	Stronger control authority on stack pose	Pre-tensioning needed
Non-stiff	1.57e1		Easier post-burn control Limited whiplash effect	Harder post-burn control Greater tail-wagging effect (strongly dependent on connections)



Relative distance during pulling and post-burn phases (non-controlled post-burn)

Tail-wagging = target angular momentum build-up, may lead to entanglement

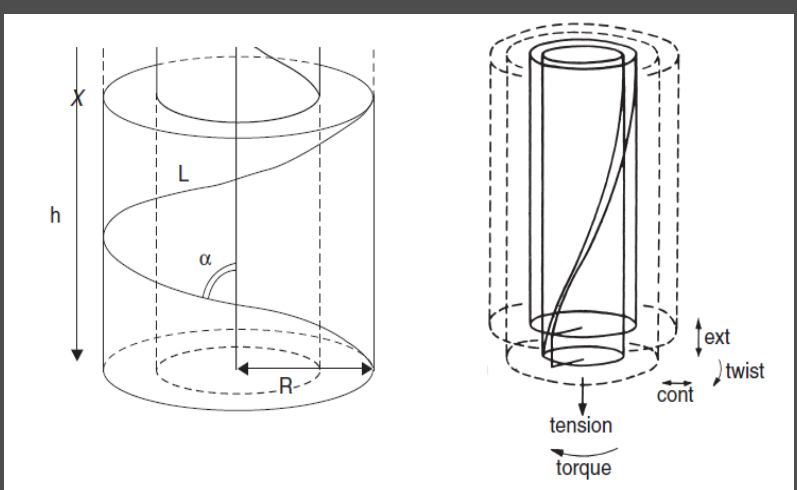
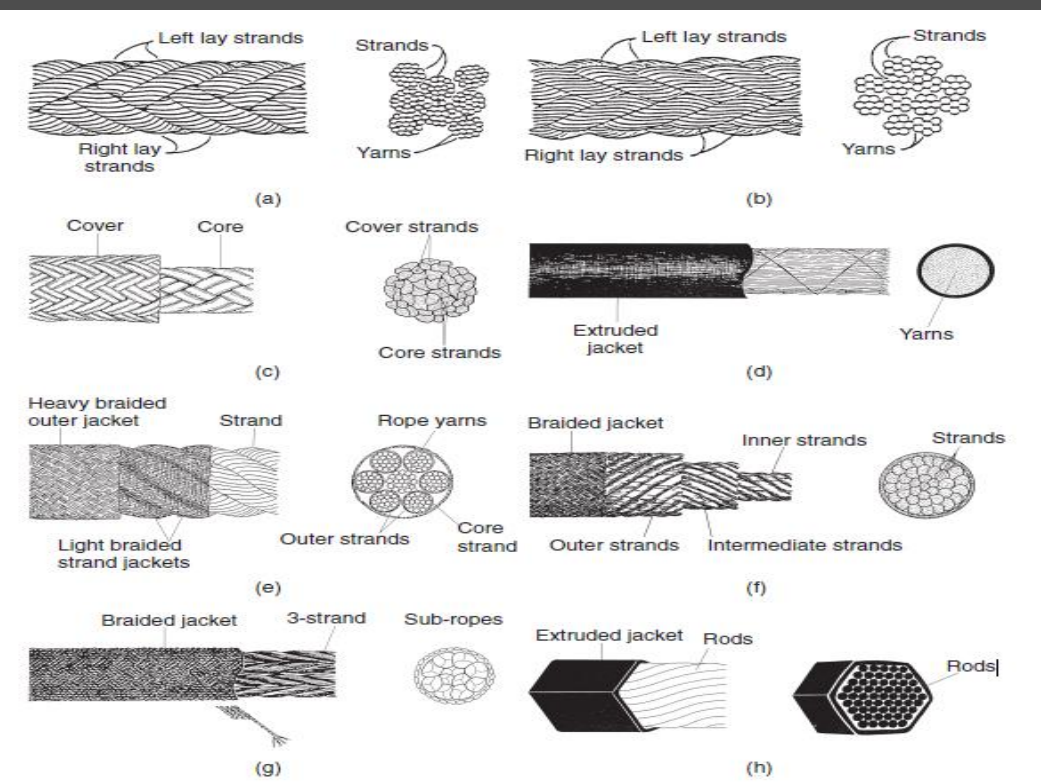


## Tether Design

### Design Drivers and Requirements

- Dynamics/Thermal simulations allow to set mechanical/thermal design drivers
- Synthetic fibers as Aramid/HPME identified as candidate materials
  - high tensile strength, high breaking tenacity
  - high impact strength
  - low density (lightweight)
  - fatigue resistance, creep and shrinkage resistance
  - dimensional stability
  - heat resistance
  - chemical resistance
- Other material requirements:
  - Stiffness (dynamic behavior): to be correctly tuned depending on expected dynamic behavior and control bandwidth
  - Foldable, spoolable
  - Stress relaxation

#### Modern rope types (different strand #, braiding technique and covers/jackets, influencing thread final properties)



Twisted yarn geometry: directly related to braid retention of strength

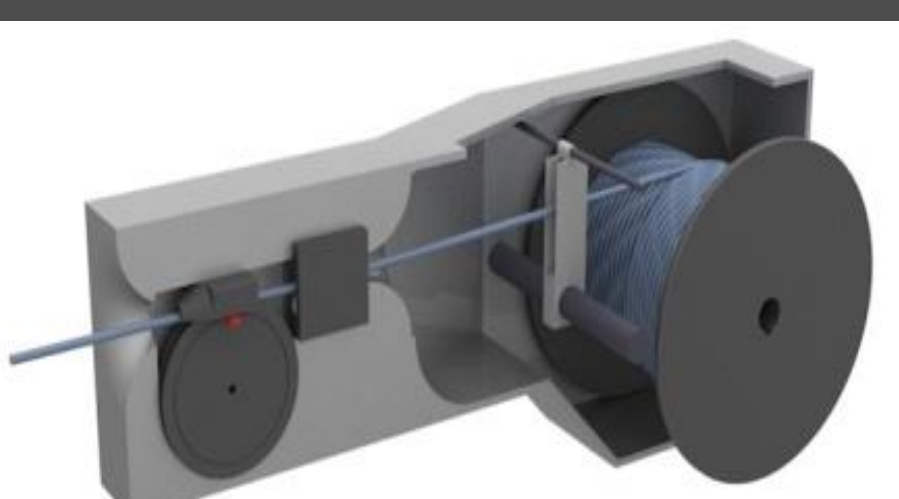
### Mechanical Properties of Candidate Materials

Material	Breaking strength [GPa]	Young's modulus [GPa]	Density [Kg/m³]	Melting/decomposing temperature [°C]	Function
Dyneema	3.7	116	970	150	Mechanical
Kevlar	3.6	130	1440	500	
Technora	3.4	73	1390	500	
Sylramic (Silicon carbide fibre)	2.6	350	3000	Over 1400	Thermal insulation
Nextel (alumina fibre)	2	190	3050	1800	

### Tether support system

#### Functions:

- Storing, releasing, holding
- Winding/unwinding
- Depend on control strategies



Active reel mechanical design

#### ACTIVE REEL

- If variable length tether control
- Critical system, more complex
- Actively controlled

#### PASSIVE SPOOL

- If fixed length tether control
- Simpler system, more reliable
- Passive releasing system
- Decoupled from chaser dynamics to limit interactions

### Thermal Analysis

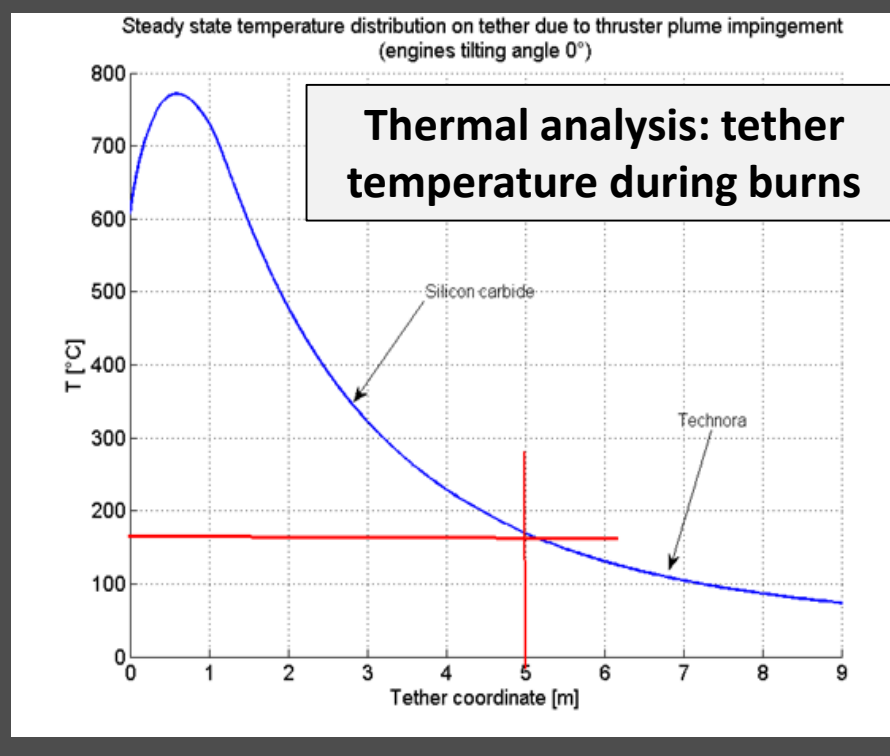
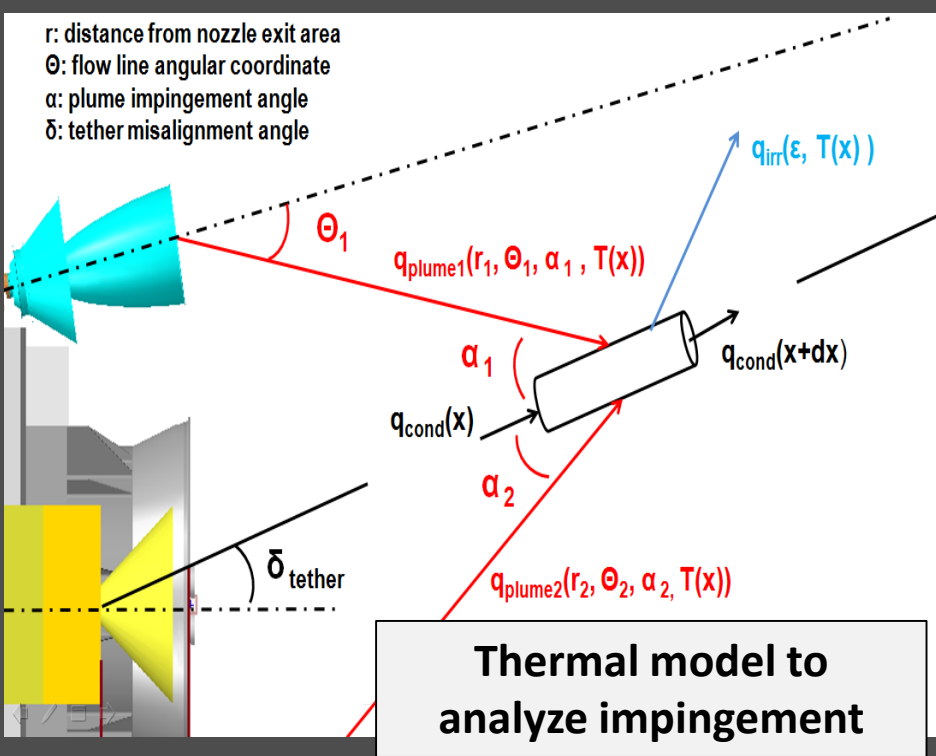
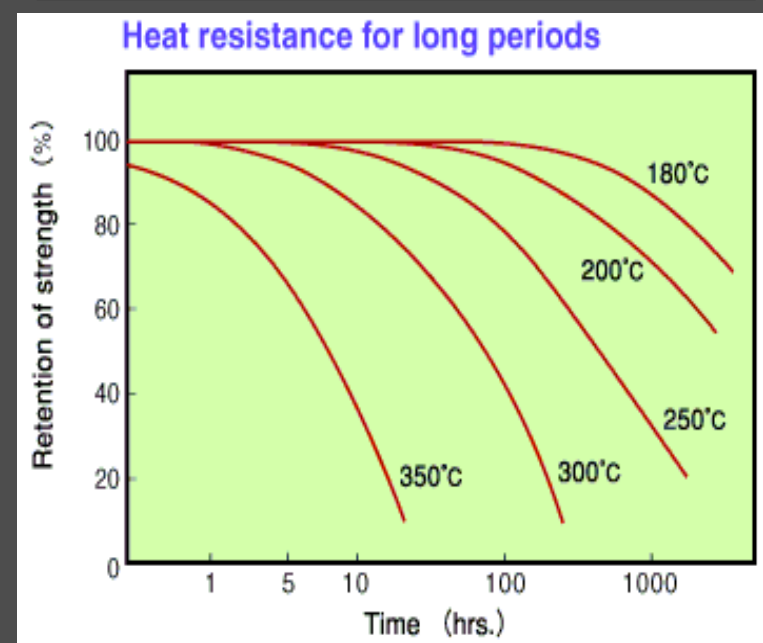
#### GAS PLUME IMPINGEMENT ON THE TETHER:

- Thrusters' exhaust plume impingement during disposal burns (limited time)
- Aramid fibers high retention of strength at high temperatures (depending on burning time)
- Thermal analysis have demonstrated that insulation is necessary for the first 5 to 10 meters of the tether
- Chemical resistance to plume impingement is also a requirement

#### Insulation's options:

- First part of the tether in Sylramic
  - Good mechanical properties at high temperatures
  - Heavier solution
  - Link Aramid/Sylramic TBD
- Nextel insulation sheath
  - Lightweight solution
  - Limited burning time – cold down phase necessary

#### Technora heat resistance: retention of strength



## Tether Testing

### Material Mechanical and Dynamical Tests

#### Fiber mechanical properties are weakened by:

- Braiding, weaving, twining
- Knotting, looping, splicing

#### Material testing:

- to characterize real parameters for design technological solutions
- to reduce the number of uncertain parameters in flexible dynamics model validation process

#### Material test campaign on 547 tex Technora braids and knotted braids:

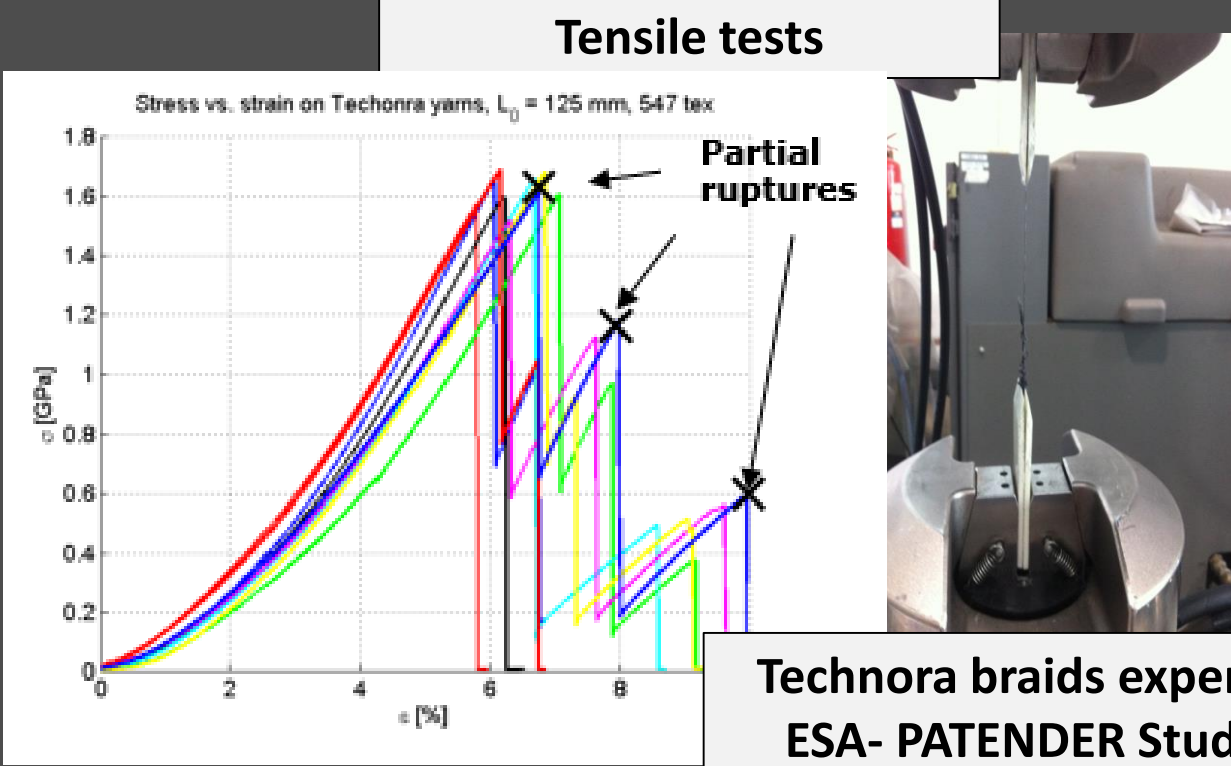
- Tensile tests
- Dynamical-mechanical testing

#### Technora braids mechanical characteristics

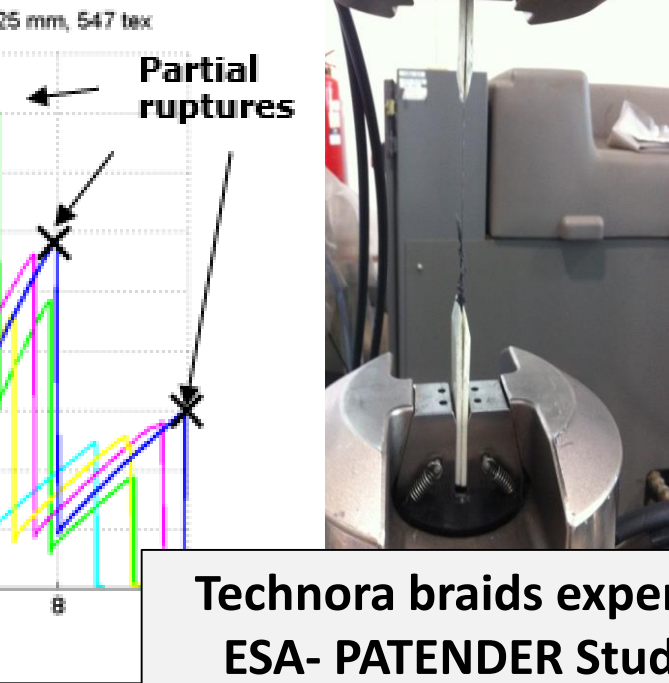
Braid Young's modulus [GPa]	25
Braid Shear Modulus [GPa]	0.118
Braid Breaking Stress [GPa]	1.6
Knot Breaking Stress [GPa]	0.5

34% of nominal fiber

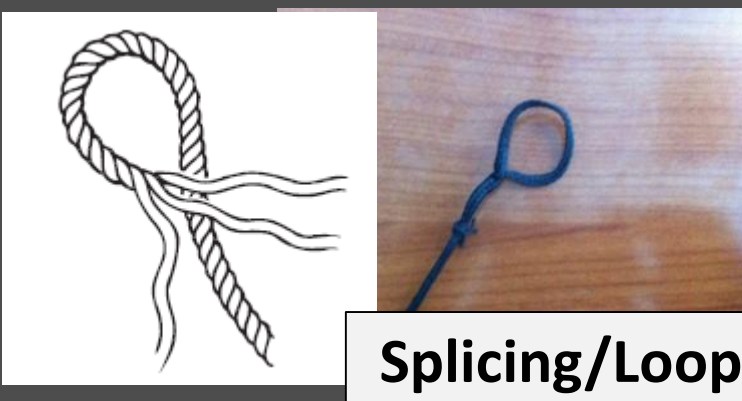
47% of nominal fiber



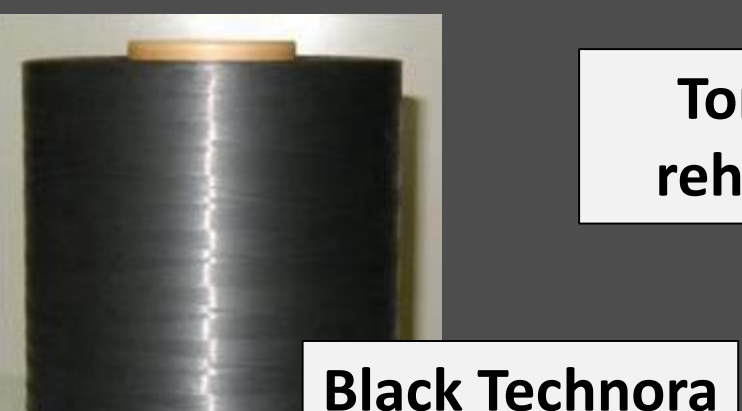
#### Tensile tests



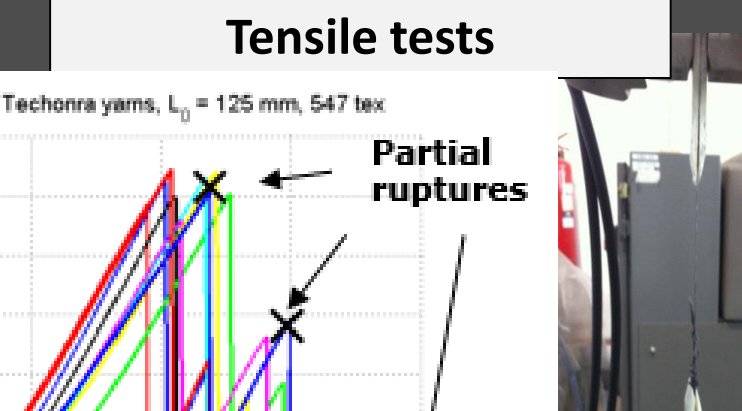
Technora braids experimental results obtained within the ESA-sponsored ESA- PATENDER Study, in consortium with GMV Spain, Prodtintec, Spain



Splicing/Looping



Torsional rehometer



Black Technora

#### Technora braids damping characteristics

Axial damping ratio [-]	0.106
Torsional damping ratio [-]	0.079
Bending ratio [-]	0.014

### Conclusions and Roadmap

#### Benefits of Tethers for Active Debris Removal:

- Safety distance
- Lightweight payload
- Centre of mass alignment with thrust axis not a constraint

#### Criticalities:

- System flexibility effects on the connected system (tether oscillations, entanglement and breakage)
- Whiplash effect (pre-tensioning)
- Post-burn bounce-back
- Atmospheric re-entry – differential drag
- Tail-wagging – tumbling target
- Gas plume impingement on tether

Closed loop GNC & thermal control have proved to be necessary and effective

#### Design and testing:

- Detailed design and testing of support system/connections/insulation
- Tests to Validate dynamics models
- Tests to characterize real parameters and verify functional requirements
- Performances quantification, requirements verification in relevant environment

#### Proposed qualification roadmap:

- Friction-less table or underwater scaled dynamics + DMA
- Microgravity testing + thermo-vacuum
- Sub-orbital flight or I.O.D.

TRL 4/5  
TRL 5/6  
TRL 7

## Subset of related references

- R. Benvenuto, S. Salvi and M. Lavagna, "Dynamics Analysis and GNC design of flexible systems for space debris active removal". Acta Astronautica, 2015.
- R. Benvenuto and M. Lavagna, "Towing tethers to control debris removal dynamics", 65<sup>th</sup> International Astronautical Congress, IAC-14-C1.6.09, Toronto, Canada, 2014.
- R. Benvenuto, M. Lavagna, A. Cingoli, C. Yabar and M. Casasco, "MUST: multibody dynamics simulation tool to support the GNC design for active debris removal with flexible elements", 9<sup>th</sup> International ESA Conference on Guidance, Navigation & Control Systems, Porto, Portugal, 2014.
- K. Wormnes, J.H. de Jong, H. Krag and G. Visentin, "Throw-nets and tethers for robust space debris capture". 64<sup>th</sup> International Astronautical Congress, IAC-13,A6.5,2x16445, Beijing, China, 2013.
- H. P. Menard, "Dynamic Mechanical Analysis – A practical introduction". 2nd Edition, CRC Press, Taylor & Francis Group, 2008.
- H. A. McKenna, J.W.S. Hearle and N. O'Hear, "Handbook of fibers rope technology". The Textile Institute, Woodhead Publishing Limited, Cambridge, England, 2004.